

Cavity and Power Coupler Integration

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Integration Issues

Why integration:

- Coupling to cavity needs to be set/determined:
 - *simulations desirable/needed*
- Coupler can be perturbation to beam:
 - *can affect coupler positioning*
- Coupler is thermal load into cold environment:
 - *important for low- β resonators*
- Coupler can be perturbation to RF properties of cavity:
 - *might require consideration of coupler during cavity design*

Cavity-Coupler Interaction: Q_{ext}

This is no straight-forward EM problem to simulate.

Analytic (Haebel):

- “Equivalent circuit model” to demonstrate how coupler can be matched to loaded Q due to beam current in SC cavity:

$$Q_{\text{ext}} = 1/2 V_{\text{acc}}^2 / ((R/Q)P_{\text{beam}})$$

- The required Q_{ext} can be set and controlled by measuring the bandwidth of a cavity/coupler system:

$$\Delta f = f_0 / Q_{\text{ext}}$$

* E. Haebel, CERN, “Couplers, Tutorial and Update”, Particle Accelerators 1992, Vol. 40, pp141-159

Cavity Coupler Interaction: Q_{ext}

Coupling simulations:

- Numerical methods (e.g. Kroll-Yu) exist for a long time. They are based on constructing a combination of standing waves in a transmission line connected to a resonator that allows to construct all possible solutions in the line.
- The original numerical approaches required a number of simulations to find the “nulls” of the standing waves in the coupler line.

* Kroll and Yu, “Computer Determination of External Q and Resonance Frequency of Waveguide Loaded Cavities”, Particle Accelerators 1990, Vol. 34, pp231

Cavity Coupler Interaction: Q_{ext}

Improved coupling simulations:

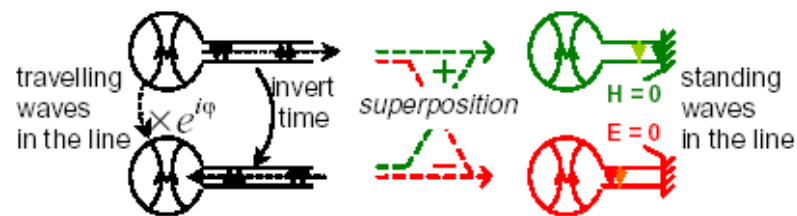
- In recent years this method has been simplified:
- Q_{ext} for coaxial lines (Pascal Balleyguier)
- Q_{ext} for waveguides (Valery Shemelin, Sergey Belomestnykh)

* P. Balleyguier, “A Straight Forward Method for Cavity External Q Computation”, Part. Accelerators, 57, p113, 1997

* V. Shemelin, S. Belomestnykh “Calculation of the B-cell Cavity External Q with MAFIA and Microwave Studio”, Cornell Publication: SRF020620-03

Q_{ext} for a Coaxial Port

Any eigen-solution of a cavity-coupler system has a standing wave (SW) contribution in the coupler pipe. It can be interpreted as the sum or difference of two TW solutions. The SW amplitude in proper scaling is twice the TW amplitude. The cavity field amplitude is TW field plus the same field at an arbitrary phase ϕ (this reflects the arbitrary position of the boundary).



For a TEM Mode:
$$Q_{\text{ext}} = \frac{\omega \iiint_{\text{cavity}} |F|^2 dv}{c \iint_{\text{line x sect}} |F|^2 ds}, \quad = \omega U_{\text{cav}}/P_{\text{line}}, \quad F \text{ is either } E \text{ or } H$$

$$Q_1 = \frac{\omega \iiint_{\text{cavity}} |E_1|^2 dv}{c \iint_{\text{ref. plane}} |E_1|^2 ds} = \frac{|1 + e^{i\phi}|^2}{4} Q_{\text{ext}},$$

Sum of the TW Solutions

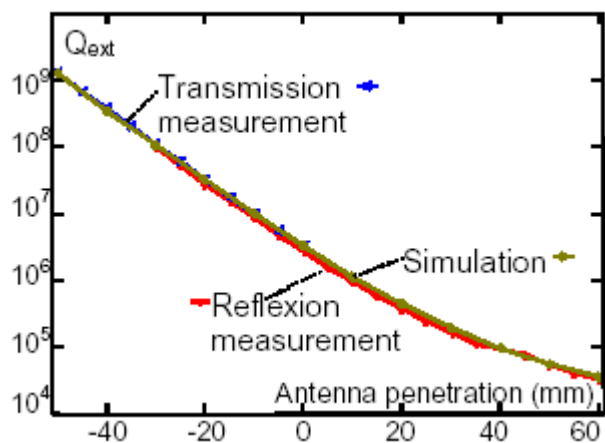
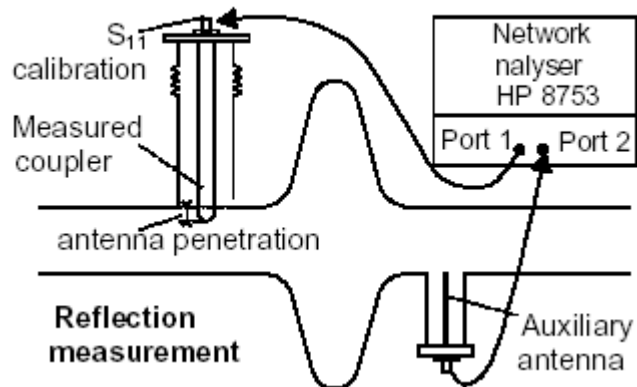
$$Q_2 = \frac{\omega \iiint_{\text{cavity}} |H_2|^2 dv}{c \iint_{\text{ref. plane}} |H_2|^2 ds} = \frac{|1 - e^{i\phi}|^2}{4} Q_{\text{ext}}.$$

Difference of the TW Solutions

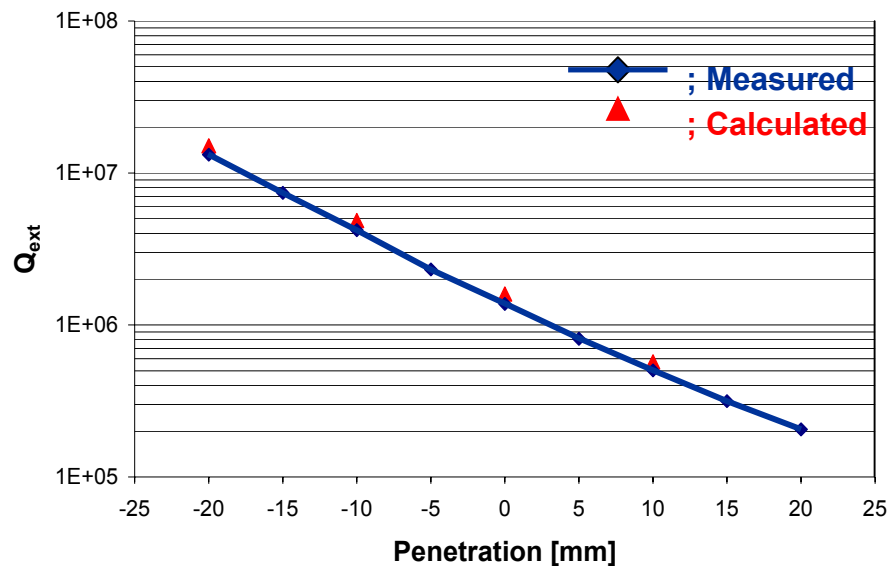
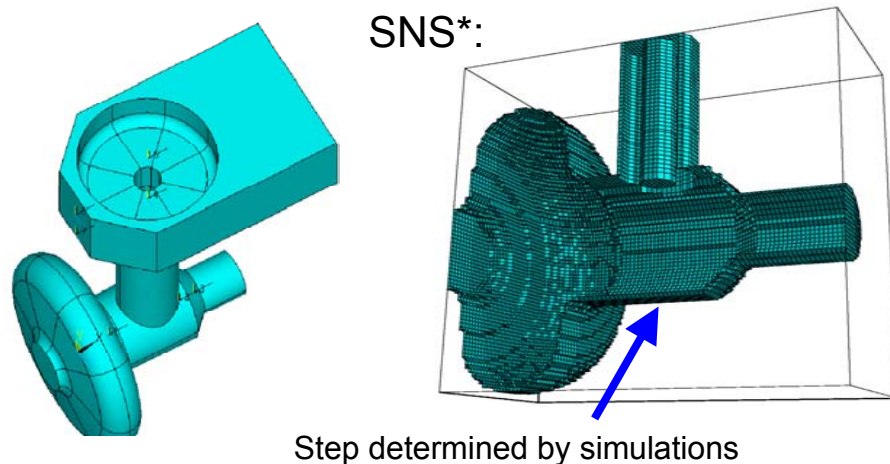
$$Q_{\text{ext}} = Q_1 + Q_2$$

Q_{ext} for a Coaxial Port (Benchmark)

APT:



SNS*:



* Challenges and the Future of the Reduced-Beta SRF Cavity Design”, Sang-ho Kim, ORNL (Linac2002)

Q_{ext} for a Waveguide Port

The method can be extended to rectangular waveguides:

Writing the $U_{\text{cav}}/P_{\text{line}}$ integrals as: $R_E = \frac{\iiint |E|^2 dv}{\iint |E|^2 ds}$ and $R_H = \frac{\iiint |H|^2 dv}{\iint |H|^2 ds}$.

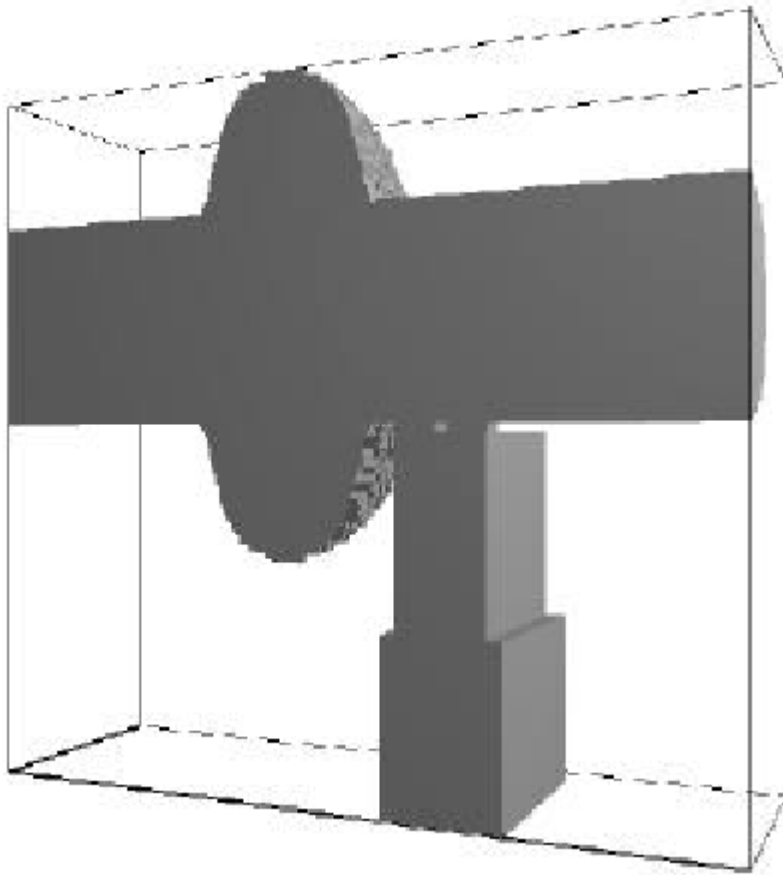
The external Q can be calculated as:

$$\begin{array}{ll} \text{TEM:} & Q_{\text{ext}} = \frac{2\pi}{\lambda} (R_E + R_H), \\ \text{TE:} & Q_{\text{ext}} = \frac{2\pi}{\lambda} \left(\frac{\Lambda}{\lambda} R_E + \frac{\lambda}{\Lambda} R_H \right), \\ \text{TM:} & Q_{\text{ext}} = \frac{2\pi}{\lambda} \left(\frac{\lambda}{\Lambda} R_E + \frac{\Lambda}{\lambda} R_H \right). \end{array} \quad \left. \begin{array}{l} \\ \\ \end{array} \right\} \begin{array}{l} \text{(Coaxial Port)} \\ \text{(Waveguide Port)} \end{array}$$

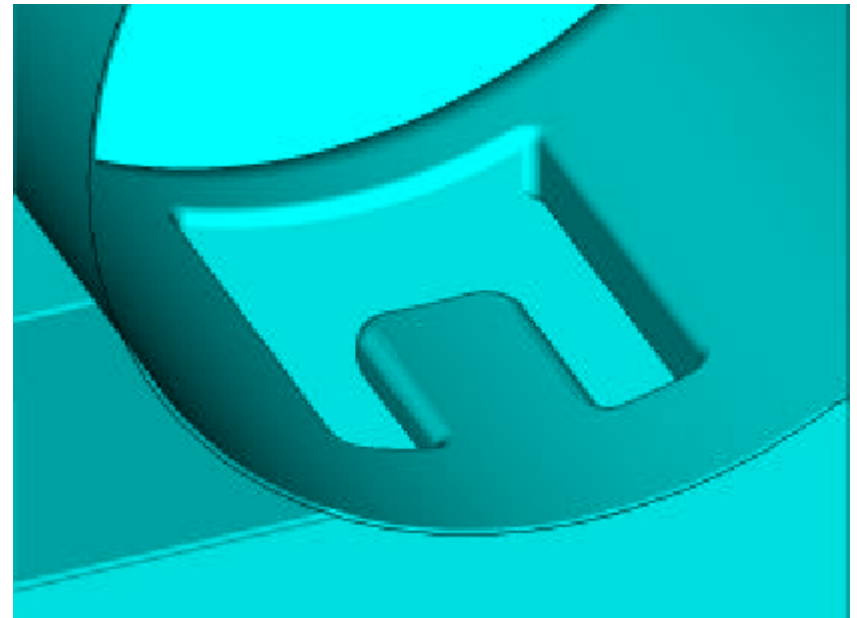
Where $\Lambda = \frac{\lambda}{\sqrt{1 - (\lambda/\lambda_c)^2}}$ is the wavelength in the waveguide

Q_{ext} for a Waveguide Port (Benchmark)

Cornell B-cell cavity



MAFIA model of full geometry



MWS model of coupling slot

Q_{ext} for a Waveguide Port (Benchmark)

	MAFIA	MWS	HFSS [13]	Equivalent circuit model	Measured
$Q_{\text{ext}}/10^5$ w/o step	2.4	2.00	2.6	(2.00)	1.84 (1.75...1.99)
$Q_{\text{ext}}/10^5$ with the step	3.5	2.53	-	2.4	2.58 (2.51...2.67)

While in MAFIA the R_E and R_H integrals have been calculated explicitly, in MWS the following analytic expressions for the line losses in a rectangular waveguide have been used:

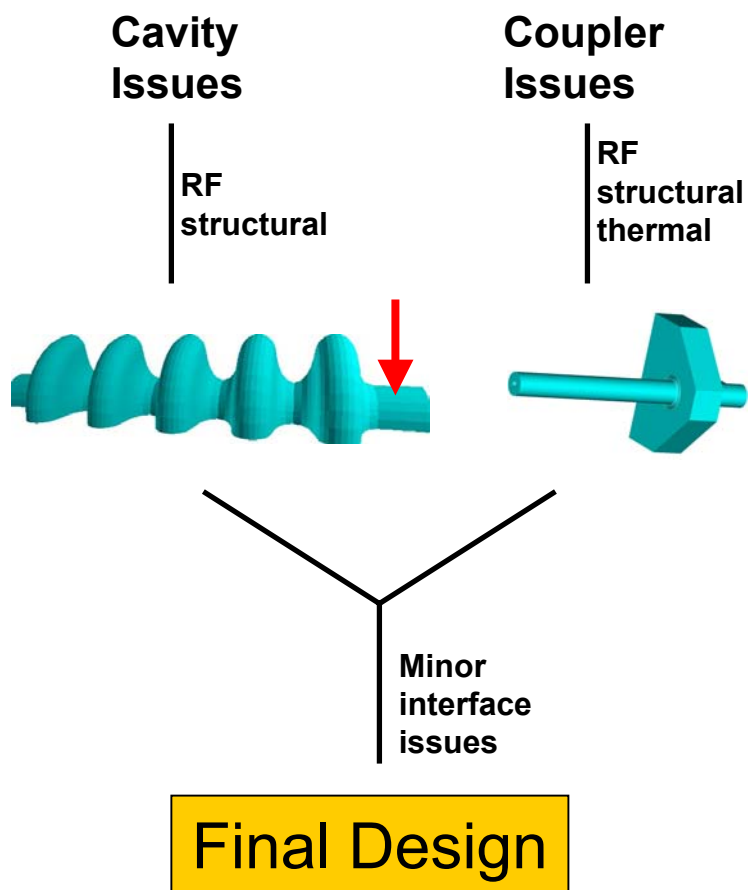
$$Q_E = \frac{8\pi\Lambda U}{\lambda^2 \epsilon_0 E_m^2 ab}, \quad Q_H = \frac{8\pi U}{\Lambda \mu_0 H_e^2 ab}$$

a and b are the waveguide dimensions, E_m and H_e are the field amplitudes in the waveguide ports.

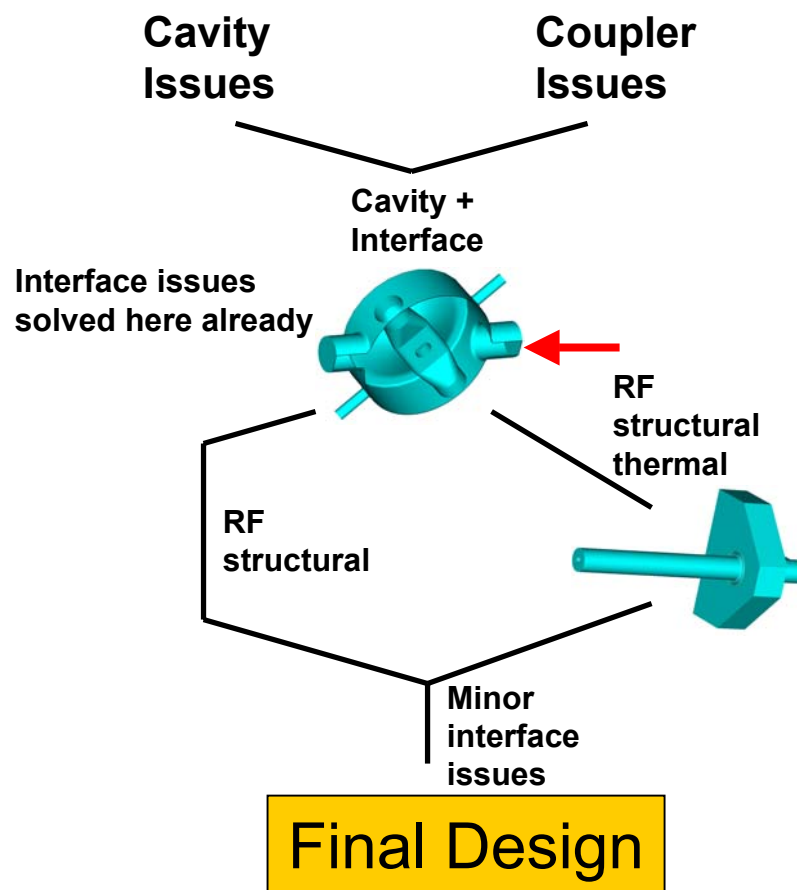
Considering the complex geometry of the slot, the better MWS result is not surprising.

Design Integration: Overview

Separate Designs

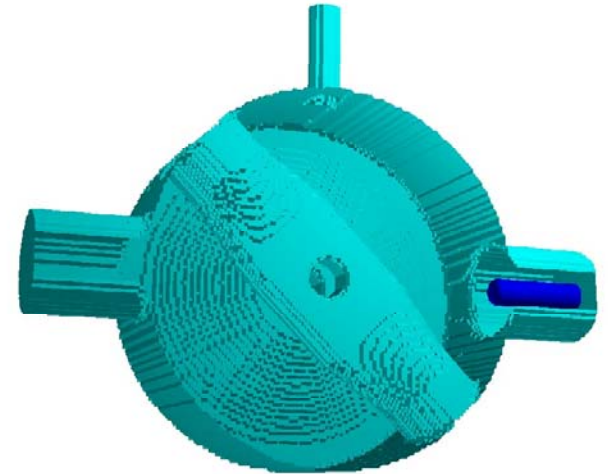
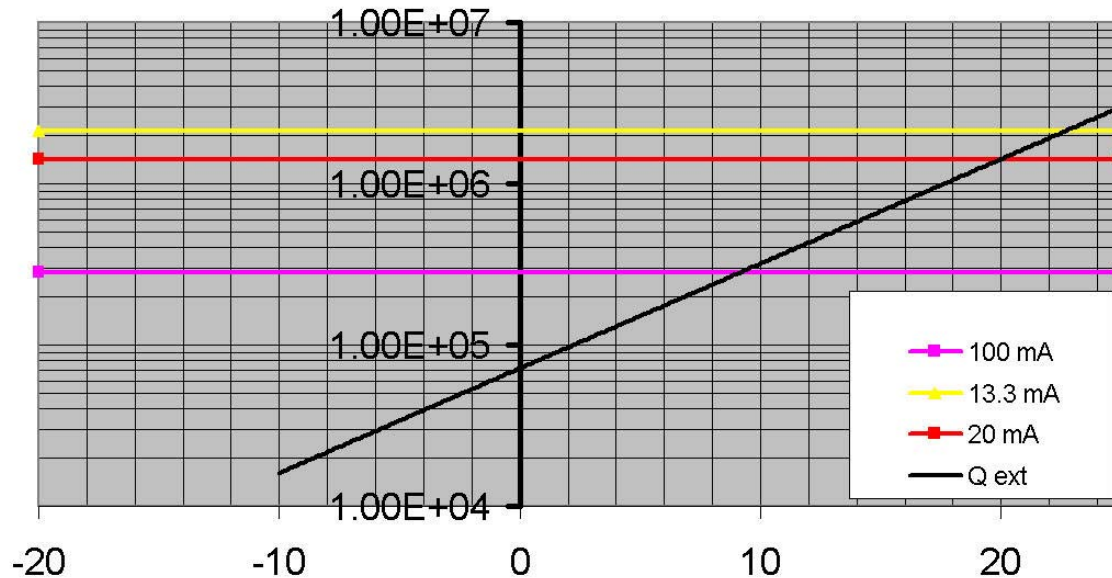


Integrated Design



Frequency Change Due to Coupler Position

Qx vs Tip for Ea=7.5 MV/m

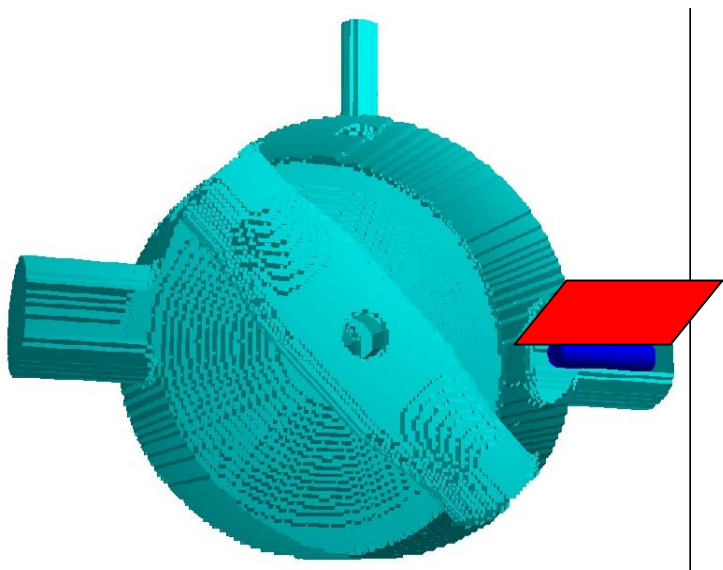


Goal: 1. Tip position
2. Frequency

I [mA]	Q _x	Δf [kHz]	z [mm]
13.3	2.13E+6	reference	23
20.0	1.42E+6	-200	20
100.0	2.83E+6	-970	9

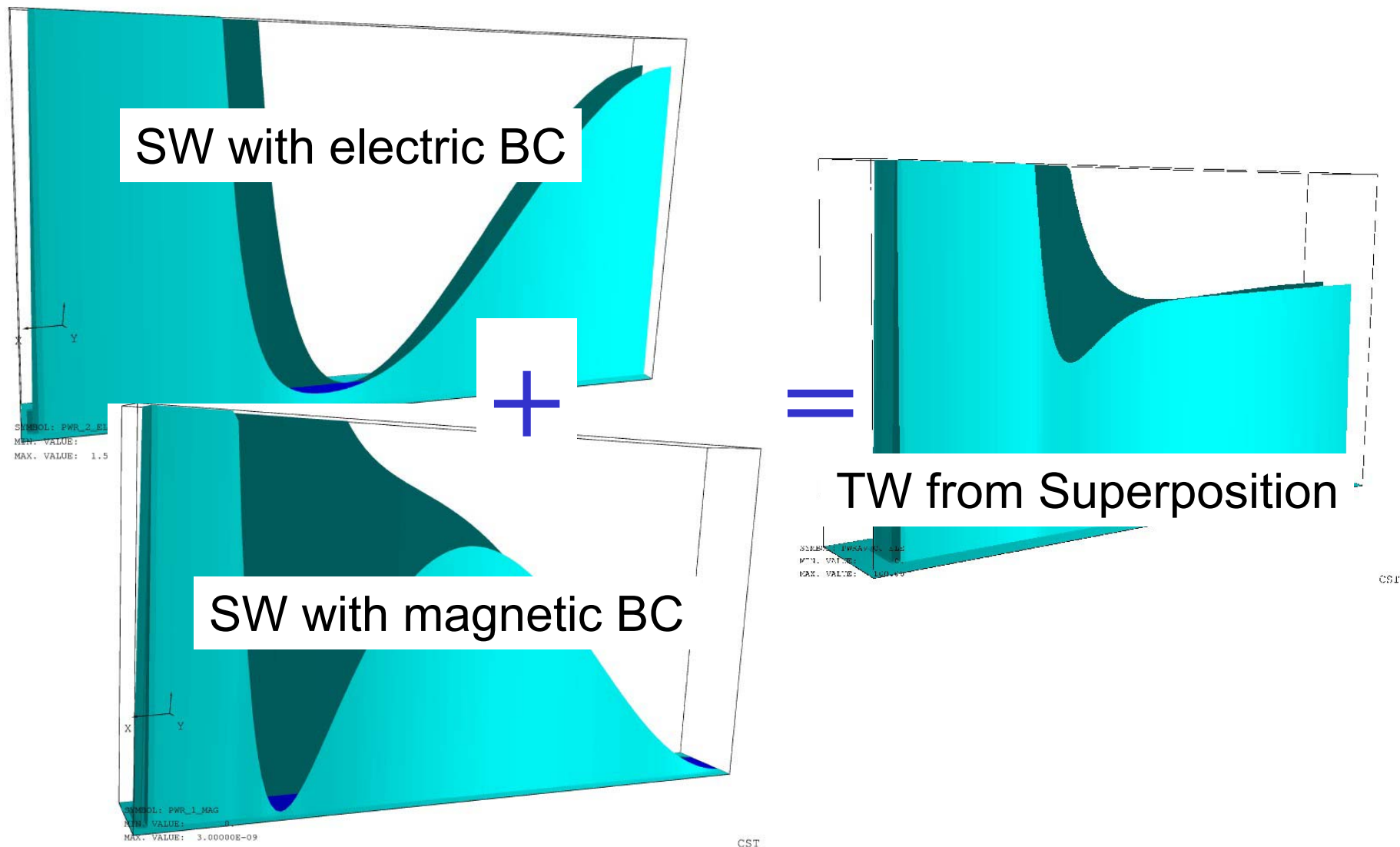
Calculation of TW Line Losses with Cavity

From the two standing wave solutions the original TW solution can also be reconstructed:

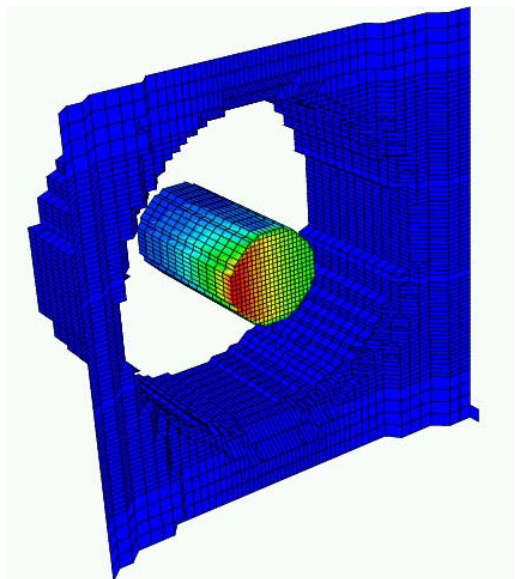


On the next slide the losses in a cut through the coaxial inner conductor are shown for the two SW solutions and for the superposition.

Calculation of TW Line Losses with Cavity



Calculation of TW Line Losses with Cavity



Radiative losses @ 8.5 kW
(7.5 MV/m, 13.3 mA)

$p_{\text{tip_max}}$	4.82 W/cm ²
$P_{\text{tip_total}}$	25.2 W
T_{tip}	52° C
P_{thermal}	0.5 W

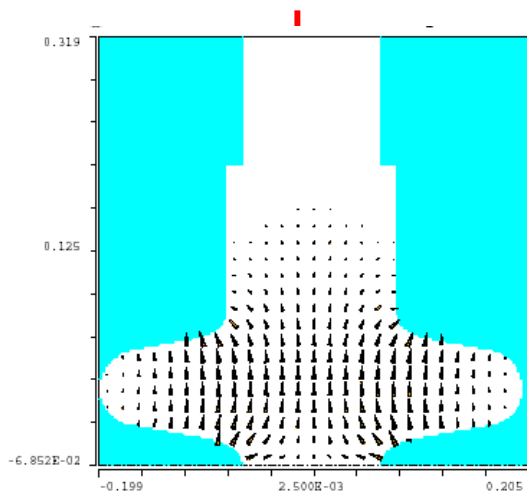
Question:

Accounting for loss contributions to cavity Q ?

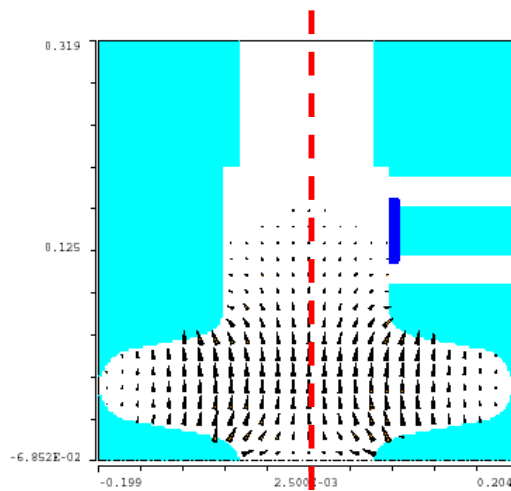
Q_0 w or w/o tip losses, tip 6 cm withdrawn

P_{cav}	$P_{\text{outer (SST)}}$	P_{antenna}	Q_0	ΔQ_0
1.0 W	-	-	3.83 E8	-
1.0 W	0.051 W	-	3.64 E8	-4.8 %
1.0 W	0.051 W	9.9 W	3.49 E7	-91.0 %

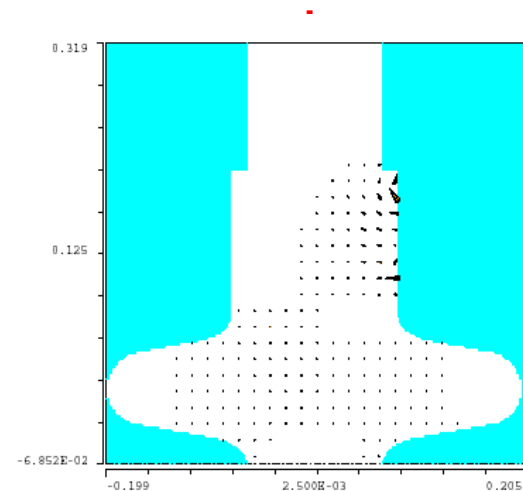
Effects on Beam Dynamics



Cavity without coupler



Cavity with coupler



Difference field

Table 1: Comparison of Longitudinal and Transverse Voltages

$r_{off-axis}$ [mm]	β	V_{long}	V_{trans}	V_{trans}/V_{long} [%]
-1.3	0.58	0.5759	$5.01 \cdot 10^{-1}$	0.1
4.0	0.58	0.5756	$8.17 \cdot 10^{-1}$	0.14
-1.3	0.64	0.4915	$8.40 \cdot 10^{-1}$	0.17
4.0	0.64	0.4911	$7.12 \cdot 10^{-1}$	0.15
-1.3	0.75	0.2590	$2.91 \cdot 10^{-3}$	1.1
4.0	0.75	0.2580	$3.04 \cdot 10^{-3}$	1.2

Table 2: Parameters/Results for the Miss-Steering Calculation

β of beam	0.75
γ of beam	1.512
field level E_0 T	5 MV/m
V_{trans} for E_0 T	7.9 kV
Bl for steering magnet	≥ 0.005 T-m
$\Delta p/p$ for steering magnet	≥ 1.3 mrad
$\Delta p/p$ from one coupler	$\simeq 0.01$ mrad

Results: APT: no issue, CEBAF: Coupler positions rotated along accelerator

Acknowledgements

This presentation represents the work based on research by the following people:

- Ernst Haebe, CERN
- Norman Kroll and David Yu, SLAC
- Pascal Balleyguier, Bruyeres de Chatel, France
- Valeri Shemlin, Sergey Belomestnykh, Cornell
- Sang-ho Kim, ORNL

I want to thank them for their contributions.

Summary

- Methods and results for issues related to the interaction of cavities and power coupler have been presented.
- For the cavity-coupler coupling accurate methods have been demonstrated to decide geometry features without empirical testing.
- Special considerations for spoke resonator designs have been shown.
- Beam dynamics considerations for coupler positioning have been motivated.

Interaction issues of cavity-coupler systems are reasonably well understood.